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1.	Your reference	RSJ07333GB
2.	Patent application number *(The Patent Office will fill in this part)*	17 FEB 2003 — 0303619.1
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	The Welding Institute Granta Park, Great Abington, Cambridge, CB1 6AL
	00774026003 Patents ADP number *(if you know it)*	
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4.	Title of the invention	IMPROVEMENTS RELATING TO JOINING OF WORKPIECES
5.	Name of your agent *(if you have one)*	Gill Jennings & Every
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Broadgate House 7 Eldon Street London EC2M 7LH
	Patents ADP number *(if you know it)*	745002

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* — YES
a) any applicant named in part 3 is not an inventor, or
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Description	15
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Priority documents	
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Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	NO

11. For the applicant
Gill Jennings & Every

I/We request the grant of a patent on the basis of this application.

Signature

Date 17 February 2003

12. Name and daytime telephone number of person to contact in the United Kingdom

SKONE JAMES, Robert Edmund
020 7377 1377

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IMPROVEMENTS RELATING TO JOINING OF WORKPIECES

The invention relates to methods for joining workpieces. The invention is particularly concerned with joining workpieces of different materials such as metals and composites but is also relevant to metal to metal joints, plastic to plastic joints, ceramic to ceramic joints and combinations thereof.

The benefits of composite structures i.e. those composed of a fibre reinforced polymeric resin, when compared to metal parts are well known:

- Higher performance to weight ratio in terms of specific strength and specific modulus
- Tailored mechanical anisotropy
- Complex smooth structure fabrication in one manufacturing operation
- High resistance to corrosion and weathering

Such properties are making such materials more and more attractive for the fabrication of secondary and primary aerospace structures. However, there are still many instances where either the ultimate property limitations or industrial conservatism and fabrication penalties have impeded their use. In view of this, compromises are sought to combine the old (metallic) with the new (composite) in the most effective way. The most common examples of this would be through a combination of mechanical fastening and adhesive bonding. Such hybrid joints are used extensively over a wide variety of industry sectors such as aerospace, automotive and building/construction.

Despite such popularity, the hybrid joint has its limitations with regard to the anisotropic properties of the composites currently employed. The most significant example being efficient and smooth load transfer between structures. Any form of mechanical fastening will require holes to be formed, which if done after the composite is

fully formed and cured, will result in local damage to fibres and potential delamination around the hole. Any load specifically borne by the fastener will induce high levels of stress around that point which could lead to rapid failure. The use of an adhesive as the second part to the hybrid system will reduce/remove such point loads and go some way to smoothing the overall stress profile within the joint area. However, loads will be only transferred across the bonded area i.e. between fibre ends (butt or scarf joint) or between the top plies of the composite (lap or T-Butt). Neither option is perfect in that scarf joints are difficult to manfuacture to maximise the bond area and simpler ply to ply joints often result in failure within the top two plies of the composite where stresses are concentrated.

At present the primary way to address this limitation is through overdesign i.e. production of over-sized hybrid joint structures to maximise bond area and increase the number/size of fasteners employed. Such tactics defeat the original objectives of using the composite material i.e. size, weight and cost savings. The well-understood properties of aerospace alloys become attractive again and limit the positive benefits of composite systems.

US-A-H788 discloses one example of a method of bonding plastic to metal in which cavities are formed in the surface of the metal by chemical etching or milling. These cavities at least in part increase in width with depth of etching so that when a plastic layer is applied, it will interlock with the metallic surface.

CA-A-2302964 (generally corresponding to EP-A-1048442 and EP-A-1197316) describes another method of joining metal to plastic in which holes are provided in the metal member through which fibres are looped.

US-A-5691391 describes the injection moulding of a plastics blade onto a spar. US-A-5118257 discloses the joining of a grooved metal member to a composite turbine blade.

In accordance with a first aspect of the present invention, a method of preparing a member for joining to a workpiece comprises forming a multiplicity of cavities and/or holes in the surface of the member whereby the surface also exhibits outward projections, by exposing the surface to a suitably controlled power beam.

In accordance with other aspects of the invention, this modified structure could also be formed through a number of other processes including mechanical processing (forming shavings still attached to the surface, drilling, cold forming, hot forming etc), material chemical processing (etching, deposition etc) and metallic foaming.

We have found that using a suitably controlled power beam such as a laser or electron beam, it is possible to create such a multiplicity of cavities and/or holes very easily and quickly and these enable the member to be joined to the workpiece and achieve a secure mechanical joint.

In accordance with a second aspect of the present invention, a member for joining to a workpiece comprises a body having a multiplicity of holes and/or cavities formed in its surface and bulk to enable it to be mechanically joined to a workpiece.

It will be appreciated from the further discussion that other inventive concepts are envisaged.

In some cases, the member may constitute a second workpiece, part of the member being provided with the multiplicity of holes and/or cavities. In other examples, the member may constitute an intermediate body for joining to other workpieces. In the latter case, part of the member will be compatible with one of the workpieces and another part of the member will be compatible with the other of the workpieces.

The invention is particularly suited to the joining of dissimilar workpieces such as metals and composites but could also be used for joining similar materials such as two metals, but typically with different physical properties.

While the holes and/or cavities assist with the mechanical joining of the member to the workpiece, a further adhesive will normally be required although one of the workpieces could be melted or plasticised to join with the member.

A new type of joining method is thus proposed. The invention addresses the limitations of current hybrid structures by embracing the general concepts of mechanical joining at a macro/micro level, typically in conjunction with adhesive bonding at a micro/molecular level. The use of an intermediate body or structure ("the insert") that will enable a graded transition to be made between the two workpieces such as metal and composite is also achieved. This structure could take a number of forms and be produced from various materials common to the metal and composite. The key to its success however is the ease in which it can be integrated into current assembly systems and the benefits associated with smooth efficient load transfer without added weight.

With most aspects of the invention, the surface and bulk of one or more of the materials to be joined will contain external features (protrusions), internal features (voids in the form of interconnecting holes) or a mixture of both. The features can be of varying dimensions and geometry and the numbers and distribution can change as one moves further away from the area to be joined. An important aspect of this relates to the fact that the holes and the external features are formed from the parent (metal) material and do not arise from an oxide modification as with anodising or some other chemical process which interacts and chemically changes the surface or the bulk of the material. An important factor is that the member is processed to enable a structure with graded mechanical properties to be achieved, for example, a controlled gradual transition between an anisotropic composite material to an isotropic metallic material.

Typically, the transition is not just a surface effect but also exists through the bulk of the material.

The modified structure could also be formed through a number of other processes including mechanical processing (forming shavings still attached to the surface, drilling, cold forming, hot forming etc), power beam (laser, electron beam, neutron beam) processing (drilling, cutting, material transport), material chemical processing (etching, deposition etc) and metallic foaming.

The shape and distribution of the protrusions and holes/channels is important in determining the optimum process. For example the holes/channels may or may not be interconnecting but they must not be isolated from the surface of the metal i.e. they must be able to be filled with a resin or adhesive before or during the bonding process.

In the example of joining a polymer composite to a metal, the material which will exhibit the modified structure may contain a mixture of holes and external protrusions which will be joined to the composite material by means of an adhesive or polymer resin applied to the surface of the material before or during the composite fabrication process. The adhesive or resin may be cured or hardened through the application of heat and pressure during the composite fabrication process in a process termed as co-curing. The adhesive/resin may also contain reinforcing fibres.

When the member forms an intermediate component or insert of reduced dimensions, it could be incorporated into the composite material to provide an edge of material to which other components can be joined at a later stage through welding, bolting or related process..

Overall, the use of an insert allows a certain degree of physical integration or intermingling between the two materials. This integration is further enhanced through the use of a joining agent which could either be the resin from a composite pre-preg or infusion process or adhesive

that is added before or during the lay-up process. The joining agent would then be used to infuse into the insert structure before and during the cure stage. Such an insert would therefore contain either or both internal pores/channels and external features which will cause mechanical entanglement of the fibres in the composite matrix at the isotropic (most probably metal) surface.

A preferred application of the method is to join polymeric composite structures to metals using a third body insert. The insert is designed such that it is graded in structure by virtue of its geometry, shape, surface and internal structure. The insert is incorporated into the composite structure during lay-up and co-cured into the structure using an appropriate adhesive or resin. The external edge of the insert is then fused to a metallic end-piece to provide the necessary functionality. The insert once in-situ is essentially a sub-composite component enabling a smooth load transfer and modulus change between the two different materials. In addition the structure of the insert is such that it will minimise CTE (coefficient of thermal expansion) mismatches between the materials.

It is envisaged that the insert could be manufactured by a third party in appropriate lengths which could be cut to size by the user when required and the incorporation of the insert can be smoothly integrated into current composite fabrication processes. It may also be necessary to pre-treat the surface of the insert in such a way as to improve and retain its adhesion characteristics during transport and storage prior to use. This might require additional processes such as etching, anodising, resin coating and adhesive infusion, all of which are well documented and familiar to persons of ordinary skill in the art of high performance composites.

In an important method of modifying the surface of the member:

1) relative movement is caused between a power beam and the member so that an elongate region of the member is melted and the melted material displaced to form a hump at one end of the region and a cavity at the other;

2) the melted material is allowed to solidify; and

3) step (1) is repeated one or more times, the elongate region corresponding to each repeat intersecting with the elongate region of step (1).

This method is described in much more detail in our co-pending British patent application no. 0222624.9 filed on 30 September 2002 and incorporated herein by reference.

The above application is particularly suitable for aerospace use where the most common materials to be used are aluminium, titanium and carbon fibre reinforced composite. Other materials could include glass or Kevlar fibre reinforced composite.

Specific examples include the use of a textured surface to embed a textured surface on one polymer and, a complimentary surface on another polymer, following which the two are joined together; and the embedding of titanium into thermoplastics.

An example of the wide applicability of the invention is that is could also be applied to bone and other biological materials.

The invention can provide an intermediate member which has different portions which are compatible with the different workpieces to be joined.

The invention is also applicable to a wide variety of joints. These include the flat butt joint, used in all examples described below, but the same co-axial joints, lap joints, scarf joints, T-joints, rebated joints, dove-tail joints etc.

Some examples of methods and intermediate bodies according to the invention will now be described with reference to the accompanying drawings, in which:-

Figure 1 is a diagrammatic side view of a joint made according to an example of the invention;

Figure 2 illustrates a first detailed example of a joint according to the invention;

Figures 3A-3D illustrate four different intermediate bodies;

Figures 4A to 4G illustrate the formation of another example of a joint according to the invention;

Figure 5 illustrates the formation of a single stepped lap joint;

Figure 6 illustrates the formation of a multistep lap joint;

Figures 7 to 10 illustrates preferred method for making cavities in a member; and

Figures 11 and 12 are photographs of a workpiece and joint respectively.

The overall appearance of a joint made according to an example of the invention is illustrated in Figure 1 which illustrates a metal sheet 1 such as aluminium welded to a composite sheet 2 utilizing an insert 3.

In the Figure 2 example, an aluminium workpiece 1 is joined to a composite workpiece 2 using a graded metal (aluminium) foam tapered insert 4 with a structure similar to bone to produce a smooth high-performance butt joint between the sheets of metal and composite 1,2. In this insert 4, the bubble/void population in the foam gradually increases from 0% i.e. a solid monolithic "skin" adjacent the metal workpiece 1 to greater than 90% at the other side of the structure. The voids/pores or slots/holes were formed using a high power electron beam (HEB) which also forms protrusions. The voids or pores are filled with infused resin. The insert 4 could be up to 200mm wide (skin to core). Ideally the bubbles/voids should be partially/fully interconnecting. The insert could have a variety of shapes ranging from a simple wedge structure to a dove-tail profile.

The advantages of such as system are:

1) Tailoring of local modulus

- Reduction of local CTE (coefficient of thermal expansion) effects
- Increase in surface area
- Increase in mechanical interlock
- Ability to fuse monolithic metallic end pieces/ structures to the skin
- Ability to integrate the insert into the composite edge during lay-up with minimal process change.

Once the insert 4 has been prepared (Figure 2(i)), it is then integrated into the composite structure 2 during lay-up such that the most porous end is embedded into the composite structure. It may also be necessary at this stage to introduce some additional resin or adhesive to fully fill the insert; this could be done via injection, infusion or by simple application during lay-up. Once this operation is complete, the composite plus insert is cured using heat and pressure usually in an autoclave under vacuum.

The composite structure now has a fully functional metallic "edge" 7 that can be joined to the metal sheet 1 using a variety of fusion techniques including laser, electron beam, friction stir welding, or resistance welding. The resultant component can now be integrated into the final structure.

In an analogous way to the bone approach of Figure 2, a similar structure could be fabricated using a modified monolithic insert profile where, after machining to produce the necessary geometry, the surface and internal structure are created using lasers or electron beams. It has been established that high power beam technology can induce suitable surface characteristics for adhesive bonding by removal of debris, controlling oxide build-up and increasing surface area. In addition both techniques can be used to perforate sheets of metal in an extensive, rapid and controlled manner. Once such processing has been

carried out a similar incorporation/fabrication route as described in connection with Figure 2 can be employed.

The benefits of this process are:

- Extremely controllable surface and perforated structure
- Ease of producing initial monolithic profile (e.g. via extrusion etc.)
- Fully interconnecting cavities
- Volume production.

Thus, as shown in Figure 3A, the metal insert 10 has a tapered portion 11 for insertion into a composite, the tapered portion 11 having been drilled to produce holes 12 (and projections - not shown) and its surface having been textured as shown at 13, both by using electron beam techniques..

Figure 3B illustrates an insert 14 similar to the insert 10 but with a tapered cavity 15 which has been drilled and textured.

Figure 3C is a modification of the Figure 3B example in which a plurality (in this case four) of tapered cavities 15A-15D have been provided.

Figure 3D is a modification of the Figure 3B example in which a cavity 15E has been formed with a rectangular cross-section.

A common practice within the structural timber industry i.e. Gulled® or gluelam technology, is to use feathered joints where the joint edge (side view) is seen to zig-zag interleaving the two edges together. This is a very strong but difficult to fabricate joint in the composites sector in that it aligns the loads directly through the composite fibres (end to end) whilst maximising surface area. Fabrication is complicated by virtue of the difficulty in aligning the composite within the "leaves" of the metal component and expensive due to metal machining costs.

The approach shown in Figure 4 sets out to simplify this process by building the insert into the composite edge

during lay-up through alternative laying down of pre-preg and then metallic sheet to produce the correct profile. The insert is then bonded in place using autoclave or vacuum bag technology using additional resin where necessary. Additional performance can be achieved through the use of surface modified/perforated metal sheet or mesh which will allow the adhesive to flow and mechanically interlock the structure. In order to bind all of the individual elements together, beam technologies such as laser or EB could fuse the structure prior to or after curing of the resin. The advantages of using such fusion process is that very little heat is dissipated laterally thereby enabling the weld to be made very close to the resin. If a gauze or mesh is used then it may also be able to carry out the fusion process via resistance heating. The gauze or mesh may be of different material to the metallic sheets. Once the insert has been produced and integrated into the composite the edge can be joined to the final component using a high volume/low heat process such as friction stir welding.

Thus, the process starts as shown in Figure 4A with an aluminium sheet 20 which is perforated at relatively high density towards its end 21, the perforation density decreasing towards the other end. A first layer of pre-preg composite 22 is laid down over the perforated end of the sheet 20 with a spacer 23 having a similar thickness to the composite layer 22 covering the remainder of the sheet 20 (Figure 4B).

Another perforated aluminium sheet 24 is then laid on top of the structure shown in Figure 4B (as seen in Figure 4C) and then a further composite pre-preg layer 25 is laid on top of the exposed portion of the layer 22 (Figure 4D). A further layer 26 of composite pre-preg is then laid on top in general alignment with the layer 22.

This process is then repeated to form a multi-laminate structure as shown in Figure 4E and this is then cured as described above so as to bond all the layers together

(Figure 4F) leaving a metal surface 27 to which an aluminium sheet 28 can then be welded (Figure 4G).

The inserts shown in Figure 3 could be machined or preferably extruded from an appropriately shaped die.

Figures 5(i) to 5(v) show the first stages in "laying up" a single step lap joint providing an insight as to how the internal and external features produced by EB or potentially other high energy beam (HEB) method would be integrated within the joint.

Figure 5(i) shows the metallic stepped insert 50 with HEB protrusions 52 and 54 and a single sheet 56 of uncured pre-preg composite material. In this case the direction of the fibres is as indicated but this is purely representational and the fibres could be in any single direction. (Indeed the pre-preg could be woven rather than uni-directional and therefore have fibres oriented in more than one direction).

Figure 5(ii) shows a side cross-section of the stepped lap joint with the first layer of pre-preg 56 in place with the protrusions 52 pushing their way through the matrix.

Figure 5(iii) shows a plan view of the same where the protrusions are represented by crosses and the slots/holes as zeros. In this particular configuration the layout of the protrusions and holes is symmetric in a grid-like pattern. This is only one representation, as the layout could take other forms such as random or graded (in position and in protrusion height), or different profiles of protrusion or slot/hole etc.

Figure 5 (iv) shows a second layer of pre-preg 58 about to be laid down. In this case this pre-preg 58 has the fibres running at 90° to the first layer 56 but this need not be the case.

Figure 5(v) shows the above with the second layer 58 in position.

The process would then be repeated as shown above with successive layers until the uncured composite is completely built up and then cured. It will be seen therefore that there is a progression from pre-preg bonded to metal

assisted by slots and protrusions to pre-preg bonded to pre-preg.

Figure 6 shows an extension of what is shown in Figure 5 where the stepped lap joint has been extended on both sides of the metallic component 60. This is a more representative structure that would be found within the aerospace industry. Again as in Figure 2, Figure 6(i) shows an insert prior to incorporation within the composite with a blow-up to clarify details. Figure 6(ii) shows a schematic representation of the insert 60 within the composite 62.

So far, we have illustrated members and workpieces having holes and projections formed by laser or electron beams typically impinging on the surface and remaining stationary while these features are formed.

An important new development is described below which we call "surfi-sculp". In the examples to be described, the surface modification is carried out by a focussed electron beam generated using a conventional electron beam source, the beam being moved relative to a substrate. Of course, as mentioned above, the substrate could be moved relative to the beam or indeed both could be moved.

Figure 7 illustrates the formation of a single swipe in a substrate 77 such as steel. The swipe commences at the location labelled 72 in Figure 7 causing the formation of a small hump. The beam then moves in a generally linear path 75 to create a melted region 73 and terminates at a point 74 where a small crater or cavity is formed. This will result in the displacement of substrate material and this is allowed to solidify, generally while the beam is creating swipe(s) in other locations. The beam can then return to this swipe location to repeat the swipe either exactly or in other ways as will be described in more detail below.

Each swipe is likely to incorporate a predominantly linear motion in relation to the work 71, whose length is typically several times greater than the diameter of the beam. If the swipe path 73 is curved, a typical minimum

radius of curvature would be comparable (but not limited) to the beam diameter.

Each swipe is capable of generating a small pool of molten material, which is translated across the surface of the work 71. In this pool, there is typically a significant surface shaping force, from the vapour pressure arising from the beam incident on the metal surface. The effect of each swipe is to displace a small amount of material. Typically a small amount of surplus material is seen as a hump 72 at the start of the swipe. A small cavity 74 of corresponding size is seen at the finish of the swipe (Figure 8).

If a second swipe is exactly superimposed over a first, both the finish cavity 74 and the start hump 72 will to a first approximation double in size (Figure 9).

If a third overlapping swipe is superimposed over the first two, the finish cavity 74 and start hump 72 will now be approximately three times larger than after the first swipe (Figure 10).

It should be noted that it is important to make use of adhesives and/or resins to complete the joining process.

Important aspects of these different examples include:

1. The use of a material with the appropriate surface and bulk structure through some type of processing to produce a mechanical interlock in addition to increasing the surface area.
2. Such a modified material will also convey appropriate thermal expansion benefits and will exhibit a graded stiffness or modulus from composite to metal.
3. The incorporation of the insert into the composite prior to its cure i.e. as a co-curing system where the insert structure is build up in-situ (Figure 4).
4. The use of an interleaved or finger joint system.

5. The use of a third body to which additional metallic functionality can be added at a later date via "conventional" fusion techniques.

Dimensions for these structures to be joined will vary but could cover virtually any composite thickness from microns to metres.

Figure 11 shows an example of a "surfi-sculpted" metal surface prior to co-curing with composite while Figure 12 shows a cross-section through a joint showing the metallic features (white), and how they have pushed themselves through two layers of composite (alternating dark (fibres running into the page) and light layers (fibres running parallel to the page)) during the laying up process.

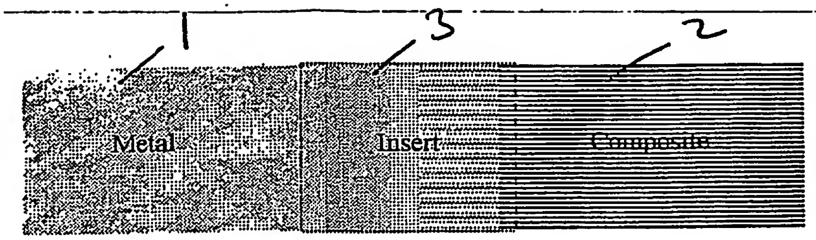
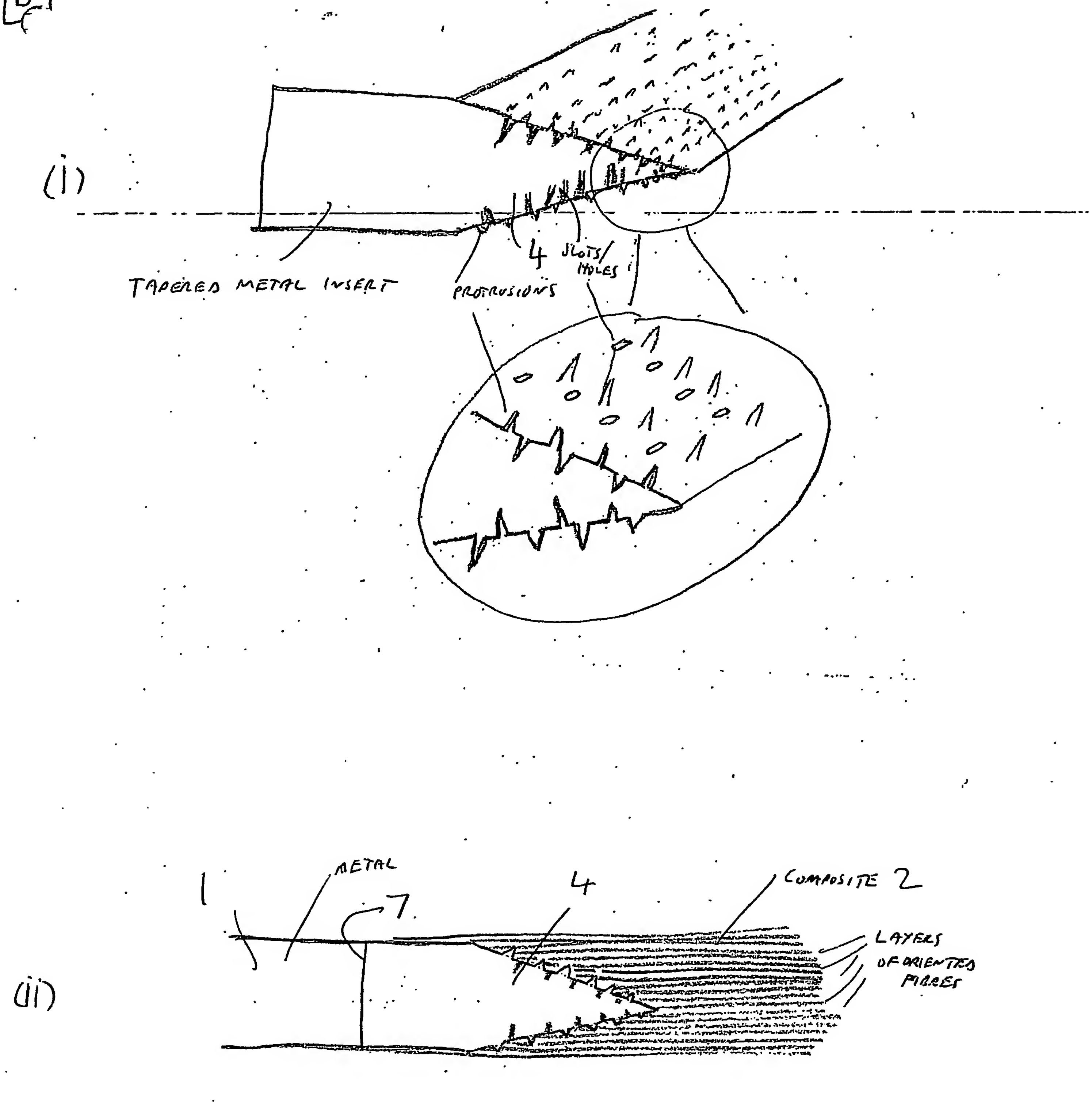


Fig.1 Graded metal to composite joint showing position of third body composite insert

B



CROSS-SECTION THRO' COMPOSITE/METAL JOINT

FIG 2

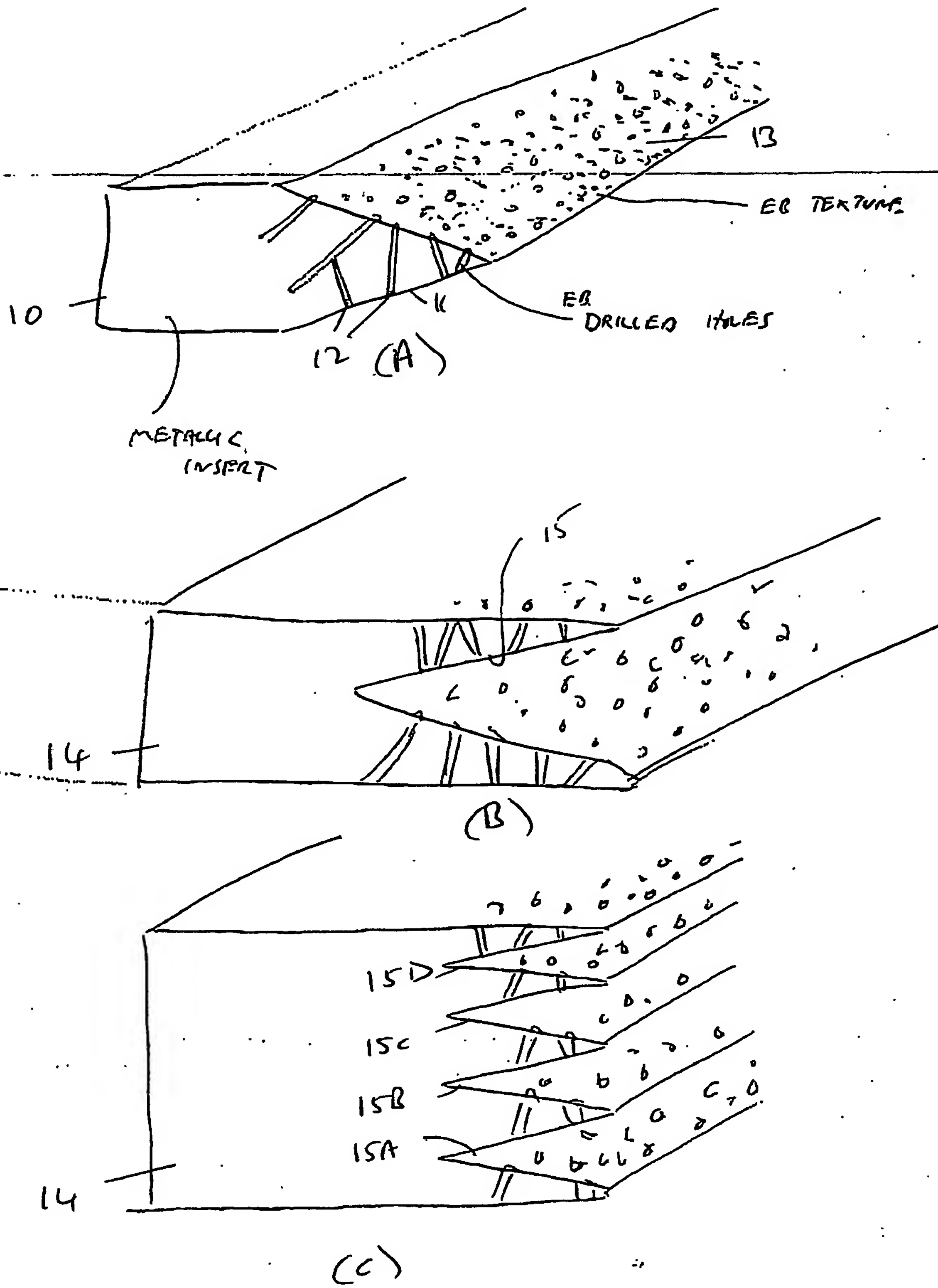
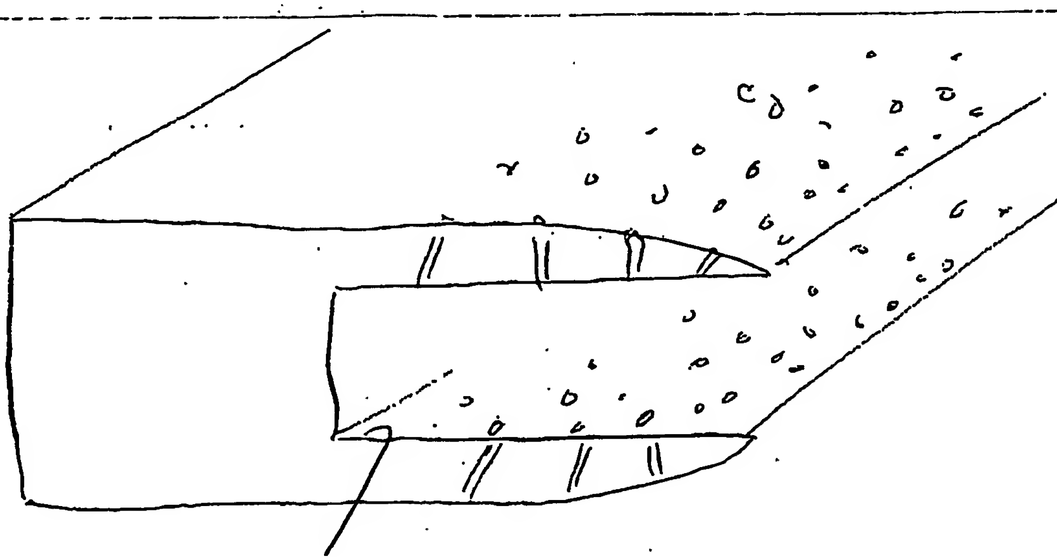

13
EB TEXTURE
EB
DRILLED HOLES
10
11
12
(A)
METALLIC
INSERT
15
14
(B)
15D
15C
15B
15A
14
(C)

FIG 3



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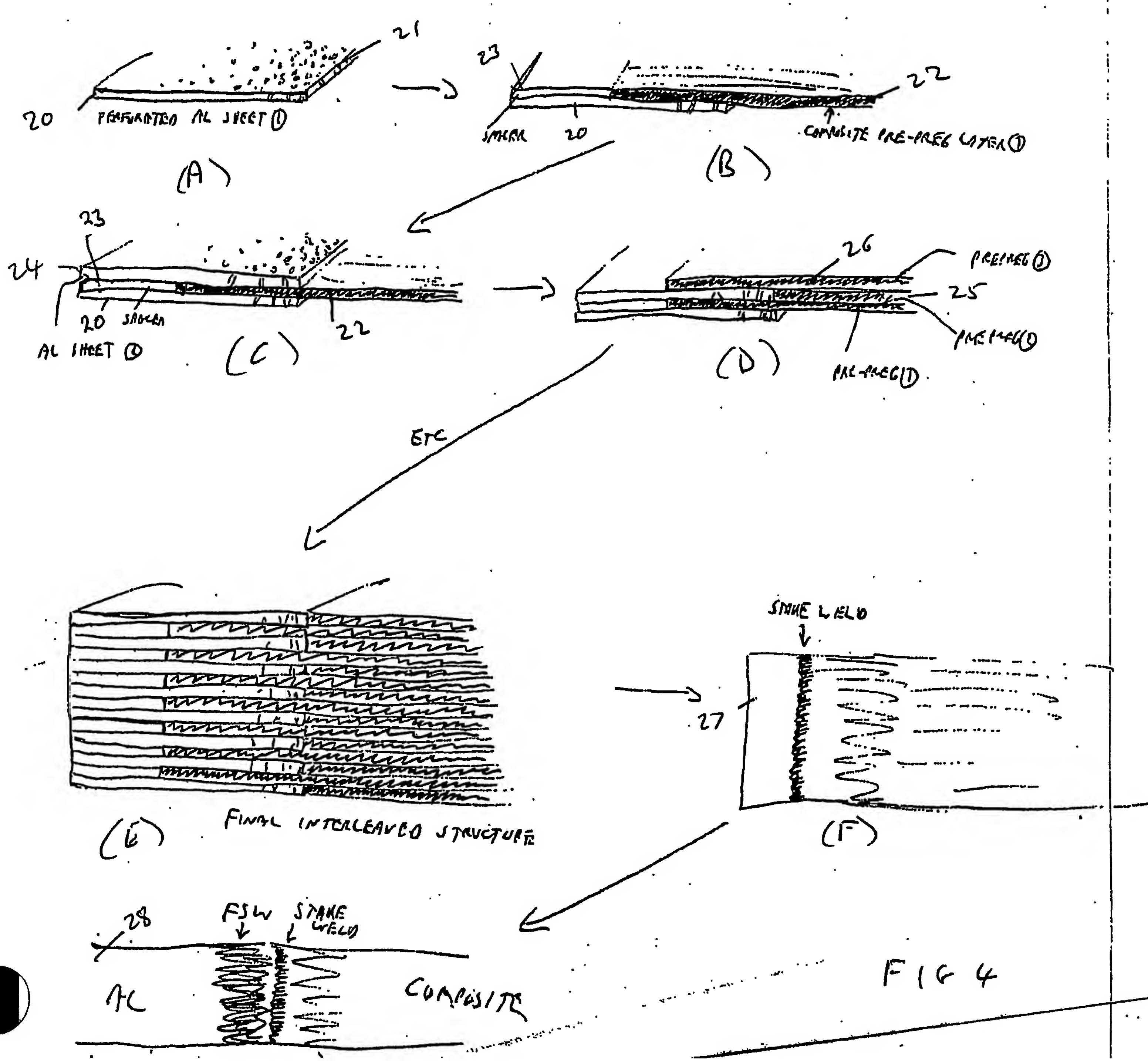

21
20
PERFORATED AL SHEET (1)
(A)
23
22
SPACER
20
COMPOSITE PRE-PREG LAYER (1)
(B)
23
24
20
SPACER
AL SHEET (1)
22
(C)
26
PREPREG (1)
25
PREPREG (1)
PRE-PREG (1)
(D)
ETC
(E)
FINAL INTERLEAVED STRUCTURE
STAKE WELD
27
(F)
28
FSW
STAKE WELD
AL
COMPOSITE

FIG 4

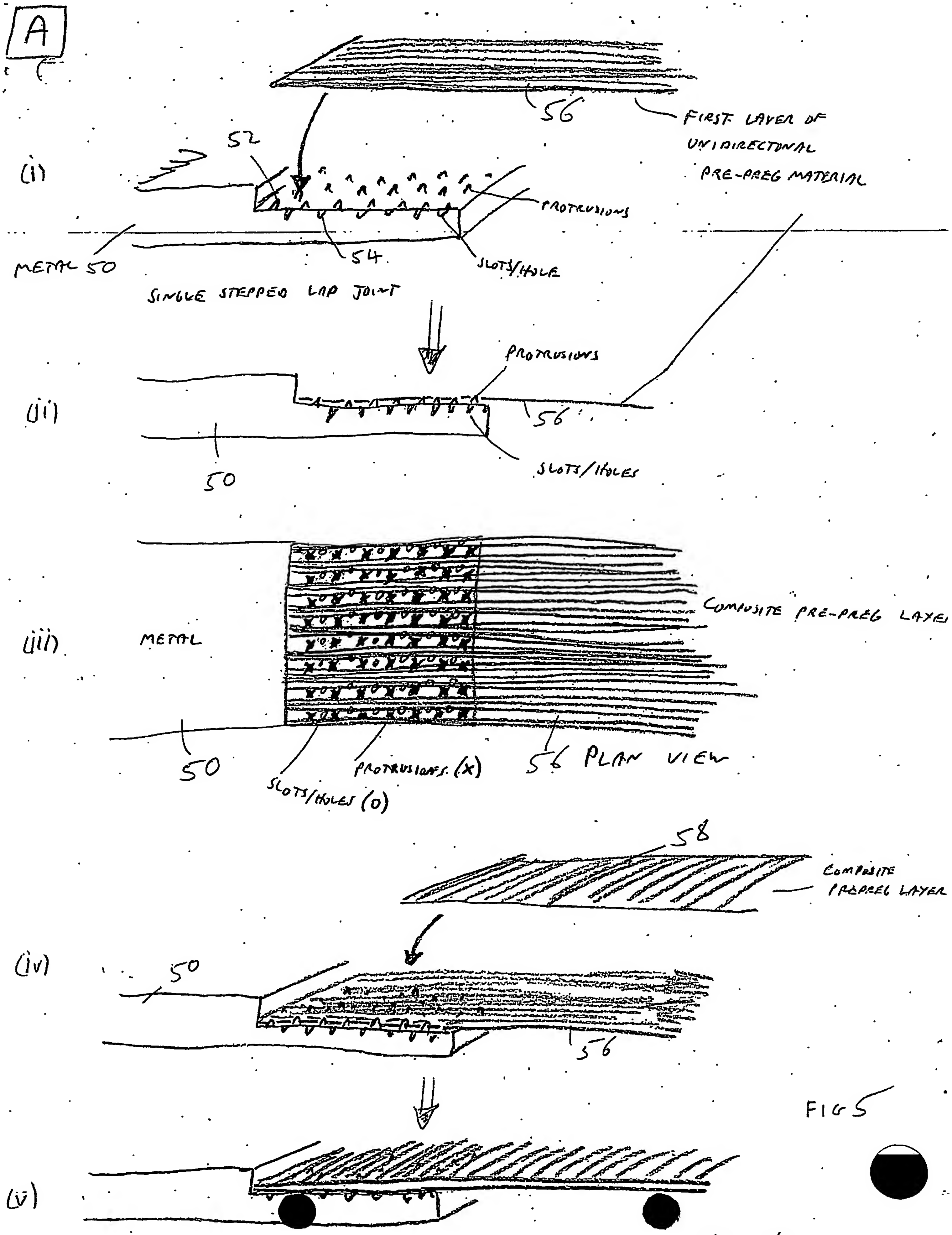
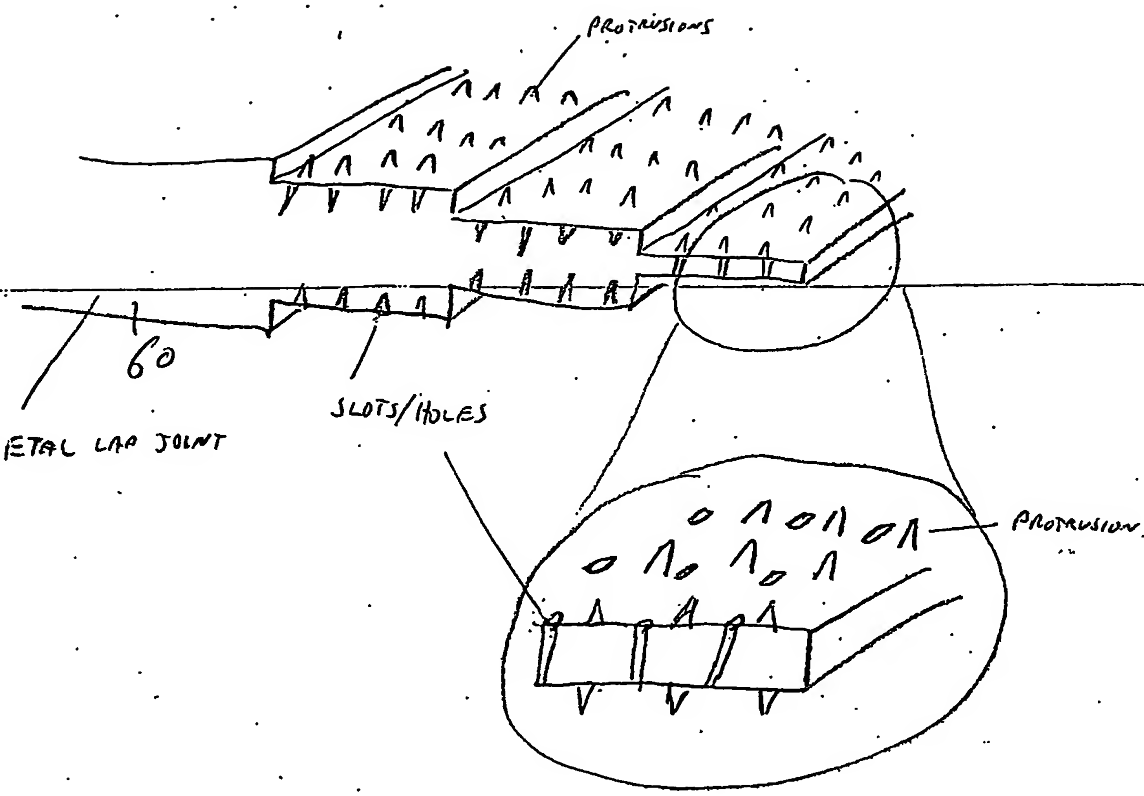

A
56
FIRST LAYER OF UNIDIRECTIONAL PRE-PREG MATERIAL
(i)
52
PROTRUSIONS
METAL 50
54
SLOTS/HOLE
SINGLE STEPPED LAP JOINT
PROTRUSIONS
(ii)
56
50
SLOTS/HOLES
COMPOSITE PRE-PREG LAYER
(iii)
METAL
50
PROTRUSIONS (x)
56 PLAN VIEW
SLOTS/HOLES (o)
58
COMPOSITE PREPREG LAYER
(iv)
50
56
(v)
etc etc

FIG 5

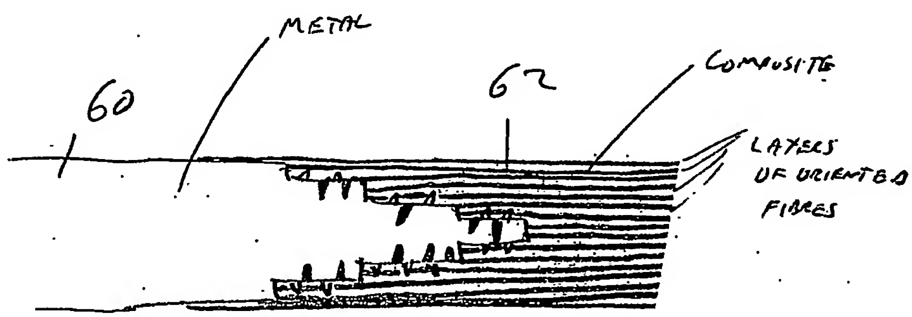
C

(i)



STEPPED METAL LAP JOINT

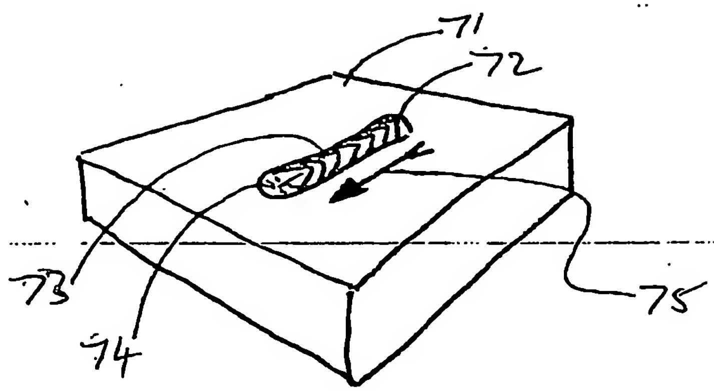
(ii)



CROSS-SECTION THRO' COMPOSITE-METAL JOINT

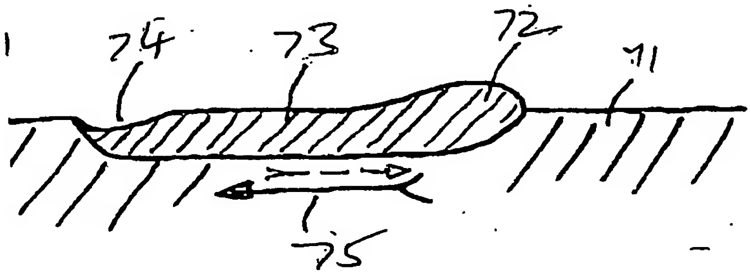
FIG 6

C



71 SUBSTRATE MATERIAL
72 'START HUMP'
73 MID-PART OF SHORT MELT-RUN OR 'SWIPE'
74 'FINISH CRATER
75 MELT-RUN OR 'SWIPE' DIRECTION

FIG 7 A SINGLE 'SWIPE'



BASE MATERIAL

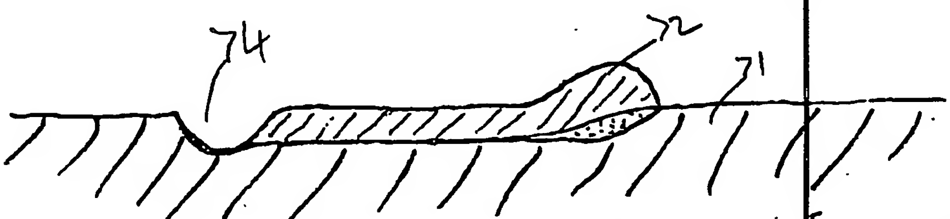
MELTED MATERI

FIG 8 A SINGLE 'SWIPE' IN CROSS-SECTIO
NOTE EFFECT, WHICH IS TO DISPLAC
MATERIAL IN REVERSE DIRECTION

2x SUPERIMPOSED 'SWIPES'

DOUBLE-MELTED MATERIAL

SINGLE-MELTED MATERIAL



BOTH 'HUMP' AND CRATER NOW LARGER

FIG 9

3x SUPERIMPOSED 'SWIPES'

TRIPLE-MELTED MATERIAL

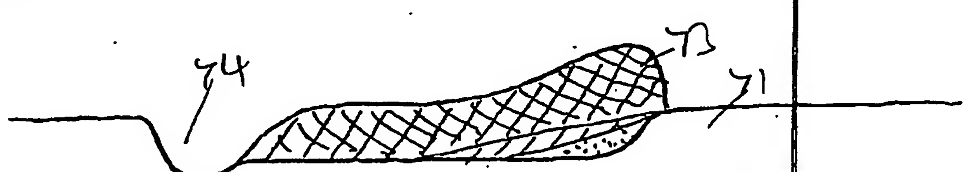


FIG 10

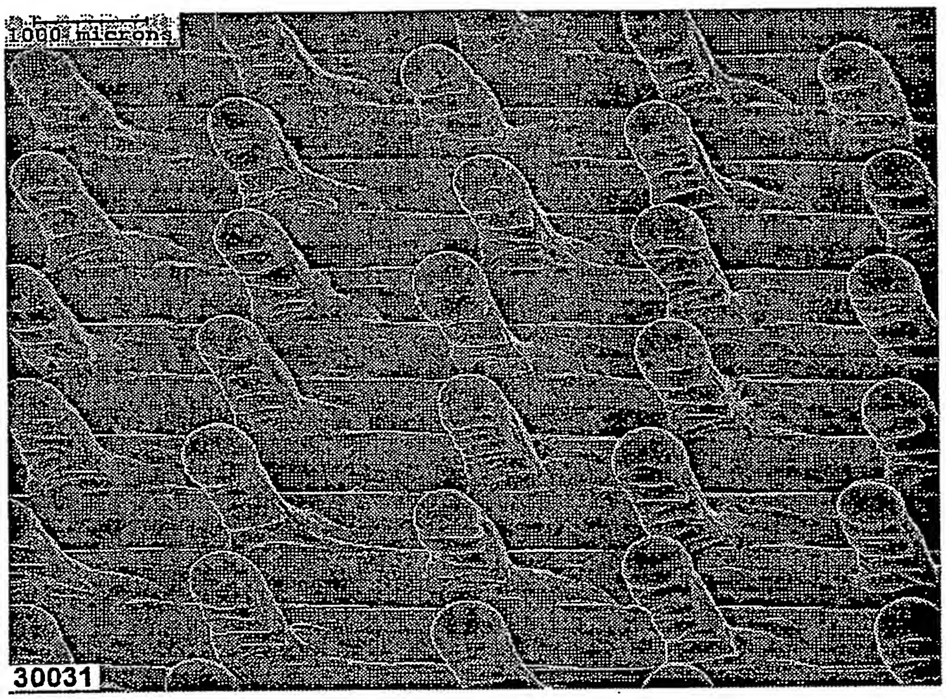


FIG 11

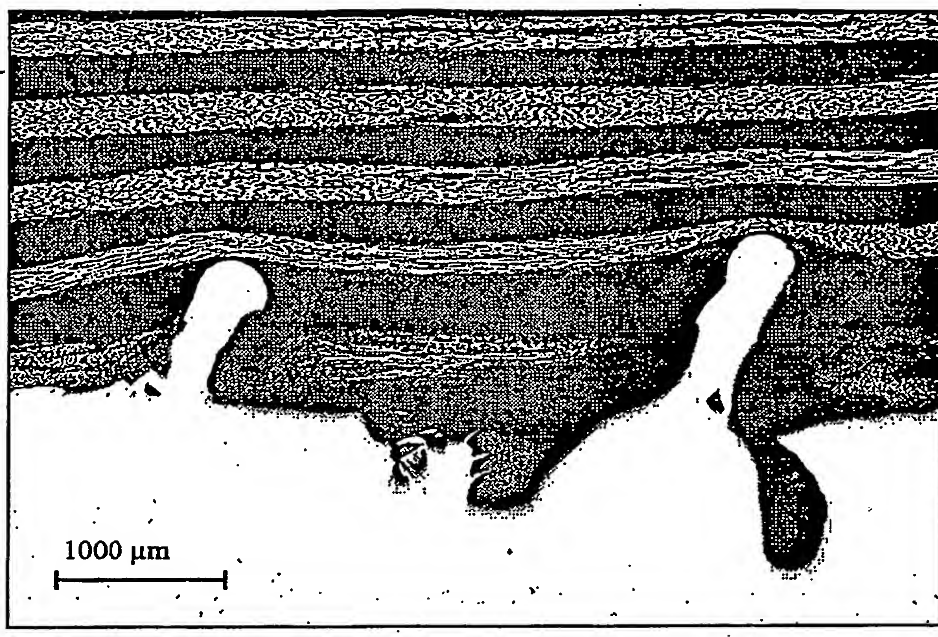


FIG 12